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Minimax Estimation of a Normal Mean Vector for Arbitrary Quadratic Loss and Unknown Covariance Matrix

by

J. Berger[1], M. E. Bock[2], L. D. Brown[3], G. Casella[4], and L. Gleser[4]

Purdue University and Rutgers University

Department of Statistics
Division of Mathematical Sciences

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ABSTRACT

Let X be an observation from a p-variate normal distribution ($p \geq 3$) with mean vector θ and unknown positive definite covariance matrix Σ. It is desired to estimate θ under the quadratic loss $L(\delta,\theta,\Sigma) = (\delta-\theta)^t Q(\delta-\theta)/tr(Q\Sigma)$, where Q is a known positive definite matrix. Estimators of the following form are considered:

$$\delta^c(X,W) = (I - c\alpha Q^{-1}W^{-1}/(X^t W^{-1} X))\, X \quad ,$$

where W is a $p\times p$ random matrix with a Wishart (Σ,n) distribution (independent of X), α is the minimum characteristic root of $(QW)/(n-p-1)$ and c is a positive constant. For appropriate values of c, δ^c is shown to be minimax and better than the usual estimator $\delta^0(X) = X$.

1. Introduction

Assume $X = (X_1,\ldots,X_p)^t$ is a p-dimensional random vector ($p\geq 3$) which is normally distributed with mean vector $\theta = (\theta_1,\ldots,\theta_p)^t$ and positive definite covariance matrix Σ. It is desired to estimate θ by an estimator $\delta = (\delta_1,\ldots,\delta_p)^t$ under the quadratic loss

$$L(\delta,\theta,\Sigma) = (\delta-\theta)^t Q(\delta-\theta)/tr(Q\Sigma) \quad ,$$

where Q is a positive definite ($p\times p$) matrix.

The usual minimax and best invariant estimator for θ is $\delta^0(X) = X$. Since Stein (1955) first showed that δ^0 could be improved upon for $Q=\Sigma=I$ (the identity matrix), a considerable effort by a number of authors (see the references) has gone into finding significant improvements upon δ^0. For the most part these efforts have been directed towards the problems where either Σ was known (or known up to a multiplicative constant) or where $Q=\Sigma^{-1}$ (a rather unrealistic assumption). For unknown Σ only a few special situations have been considered. Berger and Bock (1976a) and (1976b) found minimax estimators (better than δ^0) for problems in which Σ was an unknown diagonal matrix or could be reduced to one. Gleser (1976) found minimax estimators under the assumption that the characteristic roots of $Q\Sigma$ have a known lower bound.

In this paper the fundamental problem of completely unknown Σ will be considered. It will be assumed that an estimate W of Σ is available, where W has a Wishart distribution with parameter Σ and n degrees of freedom, and is independent of X. Let $ch_{min}(A)$ denote the minimum characteristic root of A, and define

$$\alpha = [(n-p-1)ch_{max}(Q^{-1}W^{-1})]^{-1} = ch_{min}(QW)/(n-p-1).$$

The estimators considered in this paper will be of the form

$$\delta^c(X,W) = \left(I - \frac{c\alpha Q^{-1}W^{-1}}{X^tW^{-1}X}\right)X \quad , \tag{1.1}$$

where c is a positive constant. For known Σ, estimators of this form (with $(n-p-1)W^{-1}$

replaced by $\ddagger^{-1}$) were shown to be minimax in Bock (1974) and Berger (1976b), providing $0 \le c \le 2(p-2)$. In this paper δ^c is shown to be minimax for

$$0 \le c \le c_{n,p} \quad ,$$

where the $c_{n,p}$ are solutions to equation (2.17), and are numerically calculated in Table 1 for certain values of n and p.

Table 1

Values of $c_{n,p}$

p \ n	8	10	12	14	16	18	20	25	30
3	.14	.41	.72	.88	1.03	1.10	1.23	1.51	1.53
4	.65	1.37	1.88	2.27	2.42	2.60	2.81	3.07	3.12
5		1.83	2.85	3.37	3.80	4.02	4.26	4.78	4.87
6		1.71	3.32	4.27	4.81	5.33	5.66	6.36	6.50
7			3.42	4.99	5.78	6.42	6.96	7.92	8.14
8			2.50	5.15	6.57	7.64	8.19	9.24	9.84
9				4.50	7.02	8.40	9.22	10.60	11.28
10				2.61	6.79	8.90	10.25	11.98	12.84
11					5.78	9.15	10.84	13.14	14.24
12					2.73	8.42	11.10	14.20	15.65
13						7.11	11.09	15.48	17.15
14						2.43	9.70	15.74	18.44
15							7.93	16.61	19.51
16							2.26	16.67	20.62
17								16.67	21.56
18								16.34	22.38
19									22.83
20									23.47

2. Minimaxity of δ^c

The notation $E(Z)$ will be used for the expectation of Z. Subscripts on E will refer to parameter values, while superscripts on E will refer to the random variables with respect to which the expectation is to be taken. When obvious, subscripts and superscripts will be omitted.

For an estimator, δ, define the risk function

$$R(\delta,\theta,\ddagger) = E_{\theta,\ddagger}^{X,W}\,[L(\delta(X,W),\theta,\ddagger)] \quad .$$

For notational convenience define $n^* = (n-p-1)$ and

$$\Delta_c = \Delta_c(\theta,\ddagger) = tr(Q\ddagger)[R(\delta^c,\theta,\ddagger) - R(\delta^0,\theta,\ddagger)] \quad .$$

The estimator δ^c is clearly minimax (and as good as or better than δ^0) providing $\Delta_c(\theta,\ddagger) \le 0$ for all θ and $\ddagger$.

Expanding the quadratic loss L for δ^c verifies that

$$(2.1) \qquad \Delta_c = -2E\left[\frac{c\alpha(X-\theta)^t W^{-1}X}{X^t W^{-1}X}\right] + E\left[\frac{c^2\alpha^2 X^t W^{-1}Q^{-1}W^{-1}X}{(X^t W^{-1}X)^2}\right] \quad .$$

As in Berger (1976b) an integration by parts with respect to the X_i gives

$$E\left[\frac{(X-\theta)^t W^{-1}X}{X^t W^{-1}X}\right] = E\left[\frac{tr(\ddagger W^{-1})}{X^t W^{-1}X} - \frac{2X^t W^{-1}\ddagger W^{-1}X}{(X^t W^{-1}X)^2}\right] \quad .$$

Thus (2.1) becomes

$$(2.2) \qquad \Delta_c = -E\left[\frac{c\alpha}{(X^t W^{-1}X)}\left\{2tr(\ddagger W^{-1}) - \frac{4X^t W^{-1}\ddagger W^{-1}X}{X^t W^{-1}X} - \frac{c\alpha X^t W^{-1}Q^{-1}W^{-1}X}{X^t W^{-1}X}\right\}\right] \quad .$$

Note that

$$\frac{\alpha X^t W^{-1}Q^{-1}W^{-1}X}{X^t W^{-1}X} \le \frac{\alpha}{ch_{min}(QW)} = \frac{1}{n^*} \quad .$$

Using this in (2.2) gives

$$(2.3) \qquad \Delta_c \le -E\left[\frac{\alpha c}{(X^t W^{-1}X)}\left\{2tr(\ddagger W^{-1}) - \frac{4X^t W^{-1}\ddagger W^{-1}X}{X^t W^{-1}X} - \frac{c}{n^*}\right\}\right] \quad .$$

In this expression, perform the change of variables

$$Y = \Sigma^{-\frac{1}{2}}X \quad , \qquad V = \Sigma^{-\frac{1}{2}}W\Sigma^{-\frac{1}{2}} \quad .$$

Note that V is now Wishart with parameter I and n degrees of freedom, and that $\alpha = ch_{min}(\Sigma^{\frac{1}{2}}Q\Sigma^{\frac{1}{2}}V)/n*$ Clearly (2.3) becomes

$$(2.4) \qquad \Delta_c \leq -E[\frac{\alpha c}{(Y^tV^{-1}Y)}\{2tr(V^{-1}) - \frac{4Y^tV^{-2}Y}{Y^tV^{-1}Y} - \frac{c}{n*}\}] \quad .$$

For convenience, define

$$\beta = ch_{min}(Q\Sigma) \quad , \quad Z = Y/|Y| \quad , \quad \text{and } \Sigma^* = \Sigma^{\frac{1}{2}}Q\Sigma^{\frac{1}{2}}/\beta \quad .$$

Note that $ch_{min}(\Sigma^*) = 1$. Line (2.4) can then be rewritten

$$(2.5) \quad \Delta_c \leq \frac{-\beta c}{n*} E^Y[\frac{1}{|Y|^2}E^V\{\frac{ch_{min}(\Sigma^*V)}{(Z^tV^{-1}Z)}(2tr(V^{-1}) - \frac{4Z^tV^{-2}Z}{Z^tV^{-1}Z} - \frac{c}{n*})\}] \quad .$$

To show that $\Delta_c \leq 0$ it suffices to show for all $Z \in U_p$ (the unit p-sphere) and all Σ^* with $ch_{min}(\Sigma^*) = 1$, that the following inequality holds:

$$(2.6) \qquad E^V\{\frac{ch_{min}(\Sigma^*V)}{(Z^tV^{-1}Z)}[2tr\ (V^{-1}) - \frac{4Z^tV^{-2}Z}{Z^tV^{-1}Z} - \frac{c}{n*})\} \geq 0 \quad .$$

(Note that the distribution of V does not depend on Z or on Σ^*.)

Let Γ be a $p\times p$ orthogonal matrix such that $\Gamma Z = (1,0,\ldots,0)^t$. Define $V^* = \Gamma V\Gamma^t$ and $\Sigma_Z = \Gamma\Sigma^*\Gamma^t$. Clearly V^* is also Wishart (I) and $ch_{min}(\Sigma_Z) = 1$. For convenience, let v_1 denote the (1,1) element of $(V^*)^{-1}$, v_2 denote the (1,1) element of $(V^*)^{-2}$, and let

$$\rho(V^*) = [2tr\{(V^*)^{-1}\} - 4v_2/v_1] \quad .$$

It is straightforward to verify that under the above change of variables for V, (2.6) becomes

$$(2.7) \qquad E^{V^*}\{\frac{ch_{min}(\Sigma_Z V^*)}{v_1}[\rho(V^*) - \frac{c}{n*}]\} \geq 0 \quad .$$

Since $ch_{min}(\ddagger_Z) = 1$, it is clear that

$$(2.8) \qquad ch_{min}(\ddagger_Z V^*) \geq ch_{min}(V^*) \quad .$$

Also if $a \in U_p$ (i.e. $|a| = 1$) then

$$ch_{min}(\ddagger_Z V^*) \leq a^t \ddagger_Z^{\frac{1}{2}} V^* \ddagger_Z^{\frac{1}{2}} a \quad .$$

Choosing a to be a^1, the characteristic vector of the root 1 of $\ddagger_Z^{\frac{1}{2}}$, it follows that

$$(2.9) \qquad ch_{min}(\ddagger_Z V^*) \leq (a^1)^t V^* a^1 \quad .$$

For convenience define

$$\Omega_c = \{V^*: \ \rho(V^*) < c/n^*\} \quad ,$$

let $\overline{\Omega}_c$ denote the complement of Ω_c, and let $I_A(V^*)$ denote the usual indicator function on A. Using (2.8) and (2.9) it then follows that (2.7) will hold (and δ^c will be minimax) if

$$(2.10) \quad E^{V^*} \{\frac{(a^1)^t V^* a^1}{v_1} [\rho(V^*) - \frac{c}{n^*}] I_{\Omega_c}(V^*) + \frac{ch_{min}(V^*)}{v_1} [\rho(V^*) - \frac{c}{n^*}] I_{\overline{\Omega}_c}(V^*)\} \geq 0$$

for all $a^1 \in U_p$.

To simplify this expression further, let

$$T = \begin{pmatrix} 1 & 0 \ldots 0 \\ 0 & \\ \vdots & S \\ 0 & \end{pmatrix} \quad ,$$

where S is a $(p-1)\times(p-1)$ orthogonal matrix such that

$$Ta^1 = (b, (1-b^2)^{\frac{1}{2}}, 0, \ldots, 0)^t \qquad (-1 \leq b \leq 1).$$

In (2.10), performing the change of variables $V = TV^*T^t$ (again Wishart (I)) then gives as the condition for minimaxity

$$(2.11) \quad E^V \{ \frac{(Ta^1)^t V (Ta^1)}{v_1} [\rho(V) - \frac{c}{n^*}] I_{\Omega_c}(V) + \frac{ch_{min}(V)}{v_1} [\rho(V) - \frac{c}{n^*}] I_{\overline{\Omega}_c}(V)\} \geq 0$$

for all $a^1 \in U_p$.

(Note that $v_1 = (V^{*-1})_{11} = (T^t V^{-1} T)_{11} = (V^{-1})_{11}$ and likewise $v_2 = (V^{-2})_{11}$.)

The inequality (2.11) can be rewritten

$$(2.12) \qquad c \le \frac{n^* E^V \{\rho(V) v_1^{-1}[(Ta^1)^t V(Ta^1) I_{\Omega_c}(V) + ch_{min}(V) I_{\bar{\Omega}_c}(V)]\}}{E^V \{v_1^{-1}[(Ta^1)^t V(Ta^1) I_{\Omega_c}(V) + cn_{min}(V) I_{\bar{\Omega}_c}(V)]\}}$$

Note that

$$(Ta^1)^t V(Ta^1) = b^2(V_{11}-V_{22}) + b(1-b^2)^{\frac{1}{2}}(V_{12}+V_{21}) + V_{22} \quad .$$

Hence defining

$$\tau_0(c) = E^V\{\rho(V) v_1^{-1}[V_{22} I_{\Omega_c}(V) + ch_{min}(V) I_{\bar{\Omega}_c}(V)]\} \quad ,$$

$$\tau_1(c) = E^V\{\rho(V) v_1^{-1}(V_{11}-V_{22}) I_{\Omega_c}(V)\} \quad ,$$

$$\tau_2(c) = E^V\{\rho(V) v_1^{-1}(V_{12}+V_{21}) I_{\Omega_c}(V)\} \quad ,$$

$$\tau_0'(c) = E^V\{v_1^{-1}[V_{22} I_{\Omega_c}(V) + ch_{min}(V) I_{\bar{\Omega}_c}(V)]\} \quad ,$$

$$\tau_1'(c) = E^V\{v_1^{-1}(V_{11}-V_{22}) I_{\Omega_c}(V)\} \quad , \text{ and}$$

$$\tau_2'(c) = E^V\{v_1^{-1}(V_{12} + V_{21}) I_{\Omega_c}(V)\} \quad ,$$

it is clear that (2.12), the condition for minimaxity, can be rewritten

$$(2.13) \qquad c \le \frac{n^*[\tau_0(c) + \tau_1(c) b^2 + \tau_2(c) b(1-b^2)^{\frac{1}{2}}]}{\tau_0'(c) + \tau_1'(c) b^2 + \tau_2' b(1-b^2)^{\frac{1}{2}}}$$

for all $-1 \le b \le 1$. Finally, defining $\tilde{b} = (b,(1-b^2)^{\frac{1}{2}})$

$$A(c) = \begin{pmatrix} \tau_0(c)+\tau_1(c) & \tau_2(c)/2 \\ \tau_2(c)/2 & \tau_0(c) \end{pmatrix}, \text{ and } \quad B(c) = \begin{pmatrix} \tau_0'(c)+\tau_1'(c) & \tau_2'(c)/2 \\ \tau_2'(c)/2 & \tau_0'(c) \end{pmatrix}$$

line (2.13) becomes

$$(2.14) \qquad c \le \frac{n^* \tilde{b}^t A(c) \tilde{b}}{\tilde{b}^t B(c) \tilde{b}} \quad .$$

Now for fixed $\tilde{b}$, the nonnegative solutions to (2.14) lie in an interval $0 \le c \le c_{\tilde{b}}$. This can most easily be seen by looking at (2.11) (an expression equivalent to (2.14)) and noting that the left hand side is decreasing in c. Thus defining

$$c_{n,p} = \inf_{-1 \le b \le 1} c_{\tilde{b}} \quad ,$$

it follows that if

$$(2.15) \qquad 0 \le c \le c_{n,p}$$

then (2.14) will be satisfied for all $-1 \le b \le 1$, and hence δ^c will be minimax.

To get a more explicit equation for $c_{n,p}$, note from equation (2.12) (an equivalent expression to (2.14)) that B(c) is positive definite. Hence if (2.14) holds for all $-1 \le b \le 1$, then

$$(2.16) \qquad c \le n^* ch_{min}[B(c)^{-1}A(c)] \quad .$$

Thus (2.15)$\Rightarrow$ (2.14) for all $-1 \le b \le 1 \Rightarrow$ (2.16). It is also clear that the reverse implications hold, so that

$$\{c: \ 0 \le c \le c_{n,p}\} = \{c: \ c \le n^* ch_{min}[B(c)^{-1}A(c)]\} \quad .$$

It is also easy to check that

$$c_{n,p} = n^* ch_{min}[B(c_{n,p})^{-1}A(c_{n,p})] \quad ,$$

$$c < n^* ch_{min}[B(c)^{-1}A(c)] \qquad \text{if} \qquad 0 \le c < c_{n,p} \quad ,$$

and

$$c > n^* ch_{min}[B(c)^{-1}A(c)] \qquad \text{if} \qquad c > c_{n,p} \quad .$$

Hence $c_{n,p}$ is the unique solution to

$$(2.17) \qquad c = n^* ch_{min}(B(c)^{-1}A(c)) \quad .$$

As there appeared to be little hope of analytically obtaining solutions to (2.17), the computer was used to numerically compute the solutions. For a given n and p, the values of the $\tau_i(c)$ and $\tau_i'(c)$ (and hence A(c) and B(c)) were calculated by monte carlo methods using 4000 generations of V (for n=8) to 1000 generations of V (for n=30). (Unfortunately a larger number of generations could not be used due to the considerable expense of generating V and performing the calculations involving V^{-1}.) The resulting estimated solutions, $c_{n,p}$, to (2.17) were then found and are listed in Table 1. The standard deviations of these simulated solutions ranged from about .02 (for p=3) to about .1 (for n-p = 4).

3. Comments

1. The values $c_{n,p}$ are not the largest values of c for which δ^c is minimax. Approximations were made in the proof (lines (2.8) and (2.9)) which resulted in a smaller than necessary upper bound. If one could somehow determine the "least favorable" matrix Σ_Z in (2.7), the approximations could be eliminated and the largest possible value of c obtained.

2. The estimators δ^c have a singularity as $X \to 0$. There are numerous ways of eliminating the singularity, one of the simplest being used in the following estimator:

$$\delta^{*c}(X,W) = \left(I - \frac{\min(n^* X^t W^{-1} X, c)\alpha Q^{-1} W^{-1}}{X^t W^{-1} X}\right)X \quad .$$

Through analogy with the known Σ situation, it seems quite likely that δ^{*c} is itself minimax (for $0 \le c \le c_{n,p}$) and considerably better than δ^c.

3. If the linear restriction $R\theta = r^0$ is thought to hold, where R is an $(m \times p)$ matrix of rank m and r^0 is an $(m \times 1)$ vector, then the estimators δ^c and δ^{*c} can be modified so that their regions of significant risk improvement coincide with the linear restriction. Indeed, defining $Y = RX - r^0$, $W^* = RWR^t$, and $\alpha^* = ch_{min}[(RQ^{-1}R^t)^{-1}W^*]/(n-m-1)$, Theorem 2 of Berger and Bock (1976b) can be used to show that

$$\delta_R^c = X - c\alpha^* Q^{-1} R^t (W^*)^{-1} Y / [Y^t (W^*)^{-1} Y]$$

is minimax if $0 \le c \le c_{n,m}$. The appropriate modification of δ^{*c} is the above estimator with c replaced by $\min\{(n-m-1)Y^t(W^*)^{-1}Y, c\}$.

4. If $(Q\ddagger)$ has a characteristic root considerably smaller than the other characteristic roots, then $ch_{min}(Q\ddagger)$ will be small compared to $tr(Q\ddagger)$. From the definition of $\Delta_c(\theta,\ddagger)$ and line (2.2), it is apparent that the improvement obtained in using δ^c will be quite small. The estimator, δ^c, will therefore perform best when $(Q\ddagger)$ has no exceptionally small roots. (If it is suspected that a coordinate X_i might give rise to an exceptionally small root of $(Q\ddagger)$, it would probably pay to eliminate that coordinate in the construction of δ^c, providing of course that there are at least three coordinates left.)

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Let X be an observation from a p-variate distribution ($p \geq 3$) with mean vector θ and unknown positive definite covariance matrix $\ddagger$. It is desired to estimate θ under the quadratic loss $L(\delta,\theta,\ddagger) = (\delta-\theta)^tQ(\delta-\theta)/tr(Q\ddagger)$ where Q is a known positive definite matrix. Estimators of the following form are considered:

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20 Abstract

$$\delta^c(X,W) = (I - c\alpha Q^{-1}W^{-1}/(X^tW^{-1}X))\ X,$$

where W is a p×p random matrix with a Wishart ($\ddagger$,n) distribution (independent of X), α is the minimum characteristic root of (QW)/(n-p-1) and c is a positive constant. For appropriate values of c, δ^c is shown to be minimax and better than the usual estimator $\delta^0(X) = X$.